山西繁峙新生代玄武岩地幔源区及成因探讨:元素及Sr-Nd-Pb-Hf同位素地球化学证据*

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2013-10-23 收稿, 2014-09-02 改回.

Ye L, Liu JJ, Niu YL, Guo PY, Sun P and Cui HX. 2015. Mantle sources and petrogenesis of the Cenozoic basalts in Fanshi, Shanxi Province: Geochemical and Sr-Nd-Pb-Hf isotopic evidence. *Acta Petrologica Sinica*, 31(1):161-175

Abstract The Fanshi basalts located in the vicinity of the Da Hinggan Ling-Taihangshan gravity gradient zone, represent a major component of Cenozoic basalts of the central North China Craton. Previous studies gave the Fanshi basalts whole rock K-Ar ages of 26.3 ~ 24.3Ma. The Fanshi basalts from Sumengzhuang and Yingxian two locations all show OIB-like trace element and isotopic signatures, i.e., they are enriched in incompatible elements with highly fractionated LREEs and HREEs ($(La/Yb)_N$ = 8.42 ~ 21.60) without negative Sr and Eu anomalies. They show relatively low Sr ($^{87}Sr/^{86}Sr$ = 0.703848 ~ 0.704870) and high Nd ($^{143}Nd/^{144}Nd$ = 0.512617 ~ 0.513057), Hf ($^{176}Hf/^{177}Hf$ = 0.282873 ~ 0.283001) isotope ratios, and Pb isotope ratios were $^{206}Pb/^{204}Pb$ = 17.2 ~ 17.9, $^{207}Pb/^{204}Pb$ = 15.3 ~ 15.4 and $^{208}Pb/^{204}Pb$ = 37.5 ~ 37.9. All these geochemical features, combined with petrographic observations and major element data, allow us to suggest that the Fanshi basalts were derived from small degree partial melting of asthenospheric mantle with contributions of metasomatized lithospheric mantle. Olivine and clinopyroxene dominated fractional crystallization is an important process in the petrogenesis of these basalts, which may have taken place in magma chamber of lithospheric mantle condition. The rapid ascent explains the lack of crustal contamination. Sumengzhuang samples are characterized by relatively deeper and lower extent of melting, whereas the Yingxian samples have the signature of slightly shallower and higher extent of melting. Together with studies of Cenozoic basalts in other areas near the gravity gradient zone, we suggest that the Cenozoic basalts near the Gravity Gradient zone may be originated from decompression melting of eastward asthenosphere flow when crossing the gravity gradient zone. This study offers some new perspectives on the petrogenesis of the Cenozoic basaltic volcanism in eastern China in general.
Key words Cenozoic basalts; Gravity gradient zone; Geochemistry; Formation mechanism; Fanshi region; North China Craton

摘 要 山西省繁峙玄武岩位于华北克拉通重力梯度带附近,是华北克拉通中部新生代玄武岩重要组成部分。前人全岩K-Ar测年结果为26.3~24.3Ma。对繁峙地区苏孟庄和应县两地玄武岩的地球化学特征研究表明,其微量元素和同位素均具有类OIB特征,即富集不相容元素,轻、重稀土元素分馏明显($(La/Yb)_N$ = 8.42~21.60),不存在Sr、Eu负异常,Sr同位素比值($^{87}Sr/^{86}Sr$ = 0.703848~0.704870)较低,Nd($^{143}Nd/^{144}Nd$ = 0.512617~0.513057)和Hf($^{176}Hf/^{177}Hf$ = 0.282873~0.283001)同位素比值较高,Pb同位素比值分别为$^{206}Pb/^{204}Pb$ = 17.2~17.9,$^{207}Pb/^{204}Pb$ = 15.3~15.4和$^{208}Pb/^{204}Pb$ = 37.5~37.9。结合岩相学特征和主量元素特征,我们推断繁峙新生代玄武岩是软流圈低程度部分熔融结果,并存在岩石圈物质的加入,岩浆上升

* 本文受国家自然科学基金项目(91014003、41130314)资助.
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时在岩石圈地幔条件下的岩浆房内经历了以橄榄石、单斜辉石为主的分离结晶作用,岩浆因快速上升而地壳混染程度甚低。苏孟庄碱性玄武岩具有较深的熔融深度和较低的熔融程度,而应县亚碱性玄武岩熔融深度较浅,熔融程度较高。结合重力梯度带附近其他地区的新生代玄武岩的研究,我们推测重力梯度带附近新生代的火山活动可能起源于西部软流圈地幔向东流动越过重力梯度带时的减压部分熔融,该地区广泛分布的断裂带为岩浆上涌提供了通道。本文为中国东部新生代玄武质火山活动的岩石成因学研究提供了新的视角。

关键词 新生代玄武岩;重力梯度带;地球化学;形成机制;繁峙;华北

中图法分类号 P588.145

玄武岩是地幔岩部分熔融的产物,其化学组成和同位素组成受控于地幔源区、部分熔融程度、地幔潜在温度和岩石圈厚度等诸多因素,因此可用于反演深部地幔的演化历史,是人类认识地球深部的重要窗口(Niu and Batiza, 1991; Niu *et al.*, 1996, 2001, 2011; Langmuir *et al.*, 1992; Depaolo and Daley, 2000; 徐义刚, 2006b)。华北克拉通广泛分布的中、新生代板内玄武岩为研究该地区深部地幔的性质和演化提供了天然样品。

华北克拉通东西两侧(以大兴安岭-太行山重力梯度带为界)玄武岩的时空分布存在较大的差异。东部的中、新生代玄武岩分布较广,前人研究较多(Deng *et al.*, 1998, 2004; 徐义刚, 1999; Xu, 2001; Zheng *et al.*, 2001, 2007; Zhang *et al.*, 2002; Wu *et al.*, 2003, 2006; Gao *et al.*, 2004; Xu *et al.*, 2006, 2009, 2010),而重力梯度带以西的地区,除了汉诺坝因含有丰富的幔源包体,研究程度较高以外(Fan and Hopper, 1991; Basu *et al.*, 1991; Song *et al.*, 1990; Zhi *et al.*; 1990; Choi *et al.*, 2008; Zheng *et al.*, 2009),其他地区的玄武岩直到最近几年才被重视(马金龙和徐义刚, 2004; Xu *et al.*, 2005; Tang *et al.*, 2006; Ho *et al.*, 2011; Zhang *et al.*, 2012a, b; 朱昱升等, 2012)。且西部玄武岩主要分布在重力梯度带附近,根据前人的 K-Ar 定年结果,主要属于新生代玄武岩(王慧芬等, 1988; 刘若新等, 1992; Tang *et al.*, 2006),我们推测这种时空特殊性对其成因应该有某种指示意义。

华北克拉通是世界上最古老的陆核之一,但是与全球大多克拉通不同的是,华北克拉通岩石圈发生了较大程度的减薄(Menzies *et al.*, 1993; Griffin *et al.*, 1998, 1999, 2003; Fan *et al.*, 2000; Xu, 2001; Zheng *et al.*, 2001),从古生代的200km 减薄到了新生代的 <90km(Fan and Menzies, 1992; Zheng *et al.*, 2009)。华北克拉通岩石圈减薄的认识主要是基于对中国东部地区为主的金伯利岩携带的地幔橄榄岩捕虏体和橄榄石捕虏晶的研究提出的(郑建平, 1999; Xu, 2001; Menzies *et al.*, 1993; 池际尚和路凤香, 1996; Griffin *et al.*, 1998; Fan *et al.*, 2000; Gao *et al.*, 2002),最新的研究表明东西部岩石圈地幔减薄存在时空不均一性(Xu, 2007; 徐义刚, 2006b),但是对于西部岩石圈减薄的时空范围和造成这种岩石圈减薄的机制尚不清楚,有待进一步讨论。

基于以上问题,本文以重力梯度带附近的繁峙苏孟庄碱性玄武岩和应县亚碱性玄武岩为研究对象,采用岩相学、元素及同位素地球化学等方法研究岩浆源区特征及岩浆演化过程。此外,我们还通过研究区新生代玄武岩与重力梯度带附近其他地区新生代玄武岩的对比,探讨重力梯度带附近玄武岩深部成因与地幔源区特征的异同性,并对重力梯度带附近地区新生代玄武岩的形成机制给出一个较为合理的解释。

1 地质背景

华北克拉通是世界上最古老的陆核之一(3.8 ~ 2.5Ga; Jahn *et al.*, 1987; Liu *et al.*, 1992),也是中国东部最为重要的地质构造单元。南以秦岭-大别-苏鲁造山带为界(Li *et al.*, 1993; Bai *et al.*, 2007; Meng and Zhang, 2000; Zhao and Zheng, 2009; Zheng *et al.*, 2013),北临中亚造山带(Windley *et al.*, 2007),西接青藏高原东北部,东连太平洋板块(Zheng *et al.*, 2013)。华北克拉通的东部地块和西部地块在 ~1.85Ga 时碰撞拼合,克拉通化,形成了一条南北贯穿克拉通的古元古代造山带——大兴安岭-太行山重力梯度带(Zhao *et al.*, 1999, 2001)。该带东、西两侧在地貌、地壳厚度、岩石圈厚度、地表热流值均存在明显的差异:东部地块的岩石圈较薄(<80km),地温梯度高,地表热流值高;西部岩石圈厚度大(100 ~ 150km),地温梯度低,地表热流值低(陈国英等, 1991; Niu, 2005; 徐义刚, 2006a)。在这一造山带的东缘发育着太行山断裂带。晚中生代以来大规模的伸展作用形成了华北克拉通内部广泛分布的北北东向裂谷系统:华北裂谷系、银川-河套和山西-陕西裂谷系(Ye *et al.*, 1987; Ren *et al.*, 2002; 图 1)。

前人根据对金伯利岩携带的地幔橄榄岩捕虏体和橄榄石捕虏晶的岩石学和矿物化学成分以及 Re-Os 同位素的研究指出,华北克拉通曾存在巨厚的太古代岩石圈地幔(>200km; 邓晋福, 1988; Menzies *et al.*, 1993; 池际尚和路凤香, 1996; Griffin *et al.*, 1998; Fan *et al.*, 2000; Gao *et al.*, 2002),在中生代时期发生了重要的岩石圈减薄事件,且重力梯度带东西两侧岩石圈的减薄存在时空上不均一性,导致了重力梯度带两侧岩石圈厚度的较大差异(Xu, 2007; 徐义刚, 2006a; Guo *et al.*, 2014),东部岩石圈在中生代经历了减薄(吴福元等, 2003),新生代以来逐渐增厚,而西部岩石圈主要在新生代发生减薄(徐义刚, 2006a)。

繁峙玄武岩位于华北克拉通大兴安岭-太行山重力梯度

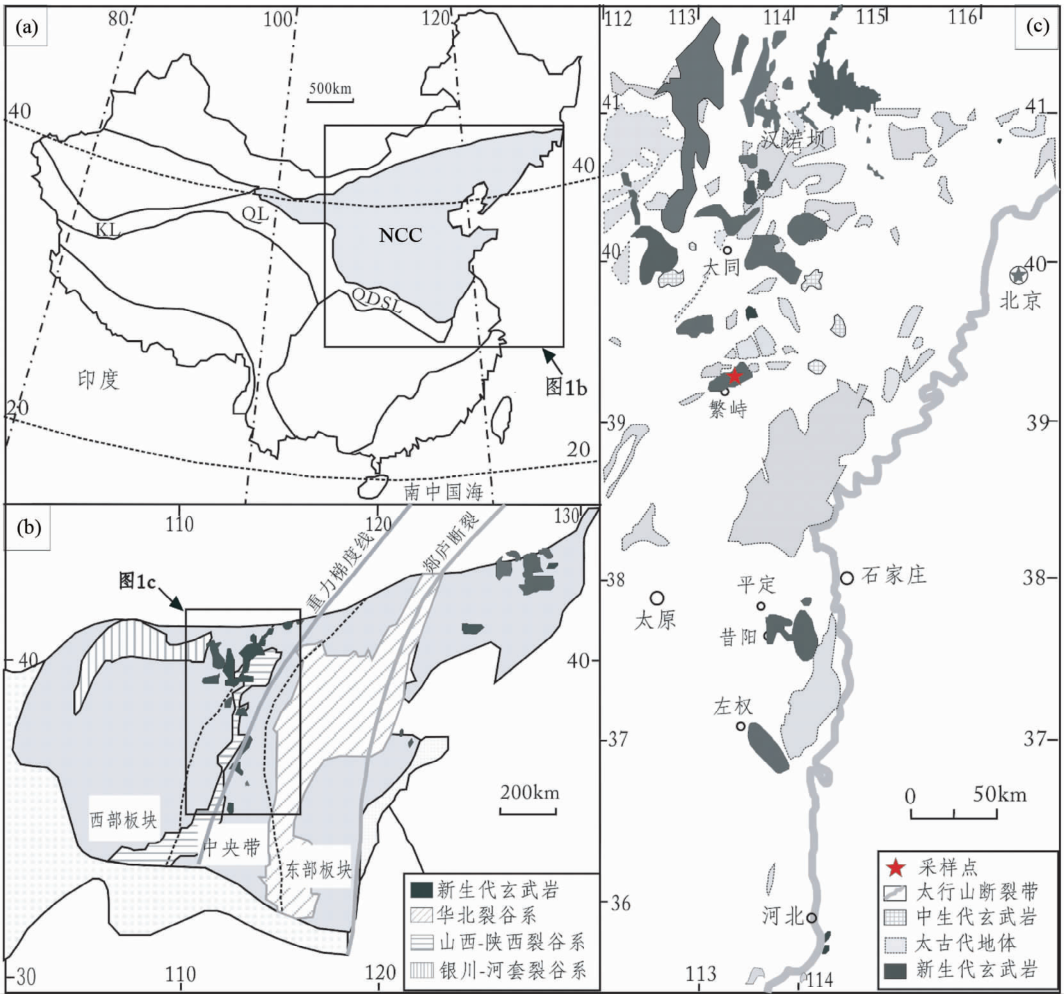

图 1　繁峙地区地质图

(a)华北克拉通位置图；(b)华北克拉通的三分(东部地块、西部地块和中央带)以及新生代裂谷系分布图(据 Zhao *et al.*, 2001 修改)；(c)太行山新生代玄武岩、中生代侵入岩和太古代地体分布图(据吴雅颂和王兴武，1978①修改)

Fig. 1　Geological map in the Fanshi region

(a) location of the North China Craton; (b) three subdivisions of the craton and the distribution of Cenozoic rift systems (modified after Zhao *et al.*, 2001); (c) distribution of the Cenozoic basalts, Mesozoic intrusive rocks and Archean terrains in the Taihang mountains

带附近，构造上位于恒山山脉东段南麓、山西断隆-五台隆起北东部。繁峙地区发育有滹沱河新裂陷，在约 30 亿年的地质历史中，经历了复杂的构造、沉积、岩浆、变质等地质作用，尤其是新生代以来，可能是太平洋板块的俯冲和印度-欧亚陆-陆碰撞的共同结果，该区地质构造运动活跃，繁峙玄武岩火山作用可能是这一大规模区域构造活动的局部响应。繁峙玄武岩之下的古老基底主要由角闪岩相到麻粒岩相的太古代片麻岩和绿岩以及碎屑岩夹层构成，之上覆盖的是静乐红土层，以及其他上新统、更新统的沉积物。玄武岩出露面积约 550km^2，厚约 800m，最大倾角 $<15°$，本文样品采集于繁峙县城城北的苏孟庄岩体和大石线 S205 上靠近应县的川草坪岩体(即后文中的应县玄武岩)，苏孟庄玄武岩主要属于碱性系列，底部携带有大量的地幔橄榄岩包体，应县玄武岩属于亚碱性系列，不含包体。全岩 K-Ar 年龄为 26.3～24.3Ma (Tang *et al.*, 2006)，属于新生代渐新世玄武岩(图 1)。

2　样品的采集和分析

苏孟庄碱性玄武岩主要分为重要的两层：顶层样品主要为灰黑色气孔状玄武岩，有些气孔中充填有方解石或其它碳酸盐矿物，呈杏仁状构造；底层样品为黑色致密块状玄武岩，其中含有丰富地幔橄榄岩包体，但与汉诺坝玄武岩不同的是，包体主要为尖晶石二辉橄榄岩相，没有发现辉石岩和麻粒岩。包体中的橄榄石蚀变较严重，一般为中粒至粗粒结构

① 吴雅颂，王兴武. 1978. 山西的近期玄武岩. 山西省地质局区域地质调查队，1－136

表 1 繁峙新生代玄武岩主量元素(wt%)

Table 1 Major elements data (wt%) of basalts from Fanshi

样品号	06	11	17	20	24	28	30	33	36	01	04
岩体	苏孟庄(SMZ11-)									应县(YX11-)	
SiO_2	45.96	45.07	45.44	43.39	46.65	47.57	46.58	44.22	50.02	49.34	50.54
TiO_2	2.25	2.46	2.38	2.39	2.54	2.26	2.34	2.39	2.26	1.92	2.07
Al_2O_3	15.51	13.88	14.24	12.72	12.93	13.59	13.68	14.33	13.41	14.00	13.84
$Fe_2O_3{}^T$	11.70	12.70	11.92	11.80	12.80	11.95	12.22	12.85	11.02	11.38	12.04
MnO	0.17	0.17	0.17	0.16	0.16	0.16	0.17	0.17	0.15	0.15	0.16
MgO	7.74	9.00	9.00	8.03	9.53	8.41	8.74	9.47	7.88	8.27	7.60
CaO	8.50	8.66	9.91	7.49	8.13	7.61	7.88	8.10	7.29	8.06	7.60
Na_2O	3.12	3.46	3.37	4.30	3.47	3.78	3.54	3.92	3.27	2.57	2.82
K_2O	1.26	1.20	1.03	0.95	0.80	1.71	1.85	2.00	1.86	1.21	1.44
P_2O_5	0.65	0.76	0.72	0.75	0.65	0.74	0.72	0.78	0.73	0.36	0.49
LOI	2.57	2.10	1.27	7.48	1.77	1.64	1.72	1.24	1.53	2.10	0.80
Total	96.84	97.35	98.18	91.98	97.68	97.79	97.72	98.23	97.88	97.26	98.58
$Mg^{\#}$	56.7	58.4	60.0	57.4	59.6	58.2	58.6	59.3	58.6	59.0	55.6
Na_2O+K_2O	4.37	4.66	4.40	5.25	4.27	5.49	5.40	5.92	5.12	3.78	4.25
Na_2O/K_2O	2.48	2.89	3.26	4.54	4.34	2.21	1.91	1.96	1.76	2.12	1.96

注:$Mg^{\#}=100\times$ molar $Mg/(Mg+Fe_{tot}{}^{2+})$

不等,呈浅黄绿色至深黄绿色,部分矿物颗粒因为氧化蚀变颜色深暗。玄武岩镜下主要为斑状结构,斑晶以橄榄石为主,橄榄石斑晶粒径可达3mm,呈自形-半自形,短柱状或不规则颗粒状,裂理发育,正高突起,少量发生伊丁石化,除橄榄石斑晶以外,还存在少量磁铁矿斑晶和较多的斜长石微晶。包体以尖晶石相二辉橄榄岩为主,橄榄石占70%,单斜辉石14%,斜方辉石12%,尖晶石3%,磁铁矿1%,与中国东部的地幔捕掳体相似。应县亚碱性玄武岩主要呈灰黑色致密块状结构,镜下斑晶主要为单斜辉石和橄榄石,单斜辉石呈聚晶出现,斜长石穿插其中,单斜辉石聚晶含量约占15%~20%,自形-半自形,干涉色可达Ⅱ级蓝,基质为斜长石微晶、磁铁矿以及火山玻璃等。

挑选较新鲜且具代表性的样品,切成薄块,用石英砂磨盘磨去锯痕及风化面,用碎样器粗碎至5mm,剔除样品中的杏仁体和斑晶,用去离子水在超声波中清洗两次,放烘箱中烘干样品,最后用玛瑙研磨仪磨至200目粉末。全岩主微量元素的分析在中国地质大学(北京)地质过程与矿产资源国家重点实验室完成,主量元素采用碱熔法,用电感耦合等离子发射光谱仪(ICP-OES)测试,测试精度1% ~3%,分析结果见表1;微量元素采用混合酸溶样法,样品测定选用Agilent 7500a型四极杆电感耦合等离子体质谱仪(ICP-MS)进行测定,分析精度依所测元素的浓度高低变化于5% ~15%之间,分析结果见表2。主微量元素详细的分析流程见Song *et al.* (2010)。

Sr-Nd-Pb-Hf同位素样品分离在中国科学院地质与地球物理研究所同位素超净实验室完成,详细的分离流程见Chu *et al.* (2009)。Sr同位素比值测试分析在天津地质矿床研究所同位素实验室用Triton热电离质谱仪(TIMS)上完成(见李潮峰等,2011),Nd和Pb同位素在中国地质大学(武汉)地质

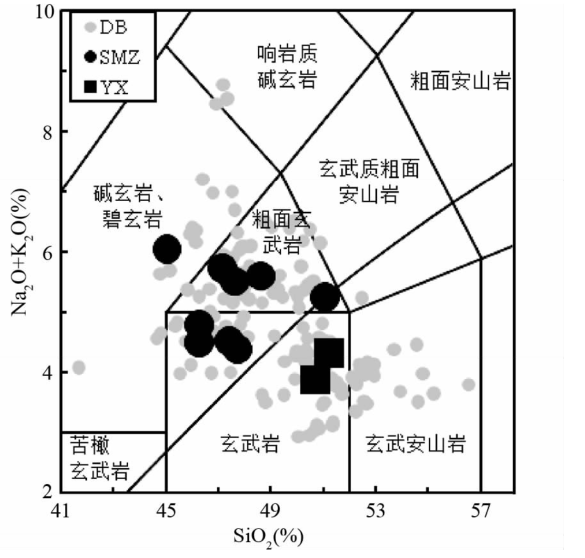

图2 玄武岩 SiO_2-(Na_2O+K_2O)图解

DB为前人重力梯度带附近的新生代玄武岩数据(Fan and Hopper, 1991; Tang *et al.*, 2006; 马金龙和徐义刚, 2004; Xu *et al.*, 2005; 张文慧等, 2005; Zhang *et al.*, 2012a, b; 朱昱升等, 2012);SMZ为采自苏孟庄的玄武岩样品,YX为采自靠近应县的川草坪岩体的样品,图3-图8同

Fig. 2 SiO_2 vs. Na_2O+K_2O diagram showing our studied samples from Sumengzhuang (SMZ) and Chuancaoping near Yingxian (YX)

For comparison, the literature data (DB) of the Cenozoic basalts near Taihang mountains are also plotted (data sources: Fan and Hopper, 1991; Tang *et al.*, 2006; Ma and Xu, 2004; Xu *et al.*, 2005; Zhang *et al.*, 2005, 2012a, b; Zhu *et al.*, 2012). SMZ are basalts we collected from Sumengzhuang; and YX are our basalts from Chuancaoping near Yingxian. Fig. 3 to Fig. 8 are same

表 2 繁峙新生代玄武岩微量元素($\times10^{-6}$)

Table 2 Trace elements data ($\times10^{-6}$) of basalts from Fanshi

样品号	06	11	17	20	24	28	30	33	36	01	04
岩体	苏孟庄(SMZ11-)									应县(YX11-)	
Li	5.40	6.25	5.20	6.35	5.52	5.38	5.95	6.95	5.37	4.89	5.06
P	2718	3214	3052	3466	2918	3056	3042	3182	3124	1516	2180
K	10098	10248	8812	8718	7012	14126	15408	16460	15784	10232	12208
Sc	17.1	17.1	23.2	15.3	17.3	14.1	15.4	15.8	14.0	21.4	18.5
Ti	14144	16332	15536	16882	16926	14428	15218	15132	15558	12632	14226
V	184	178	223	176	194	152	166	160	159	186	178
Cr	98.5	156	206	156	178	148	165	175	159	210	183
Mn	1085	1133	1172	1162	1164	1100	1115	1112	1065	1052	1104
Co	38.1	45.5	44.1	44.6	50.0	39.9	42.5	44.0	41.0	40.4	44.1
Ni	78.6	150	122	133	179	126	135	156	131	116	161
Cu	46.6	46.4	45.1	42.9	45.5	39.1	39.2	43.2	37.5	45.2	51.4
Zn	96.1	106	101	111	107	125	113	120	107	100	98.1
Ga	19.2	20.2	18.5	22.1	21.3	21.0	21.8	21.5	20.7	18.2	18.9
Rb	16.5	21.8	21.2	8.3	18.1	14.2	15.6	15.4	14.8	11.4	10.9
Sr	804	800	962	927	825	902	976	911	1000	464	613
Y	22.5	20.5	22.6	20.6	18.8	19.0	19.5	19.6	16.9	18.9	18.2
Zr	263	274	261	308	258	322	320	316	340	178	223
Nb	53.3	64.3	56.1	71.2	58.1	71.2	69.4	69.0	70.1	31.8	38.9
Cs	0.87	0.34	0.62	0.34	0.37	0.40	0.42	0.42	0.41	0.11	0.15
Ba	5368	409	868	500	357	520	512	521	543	387	424
La	32.6	33.7	34.7	38.4	28.6	36.6	36.1	35.7	34.5	17.8	22.6
Ce	66.4	66.8	71.1	77.1	58.0	74.3	73.2	73.0	71.8	38.1	46.2
Pr	8.72	8.73	9.27	9.96	7.68	9.64	9.65	9.54	8.68	5.22	5.80
Nd	32.8	33.4	35.1	38.1	30.0	36.4	36.8	36.4	36.1	20.7	24.7
Sm	6.57	7.04	7.01	7.85	6.48	7.43	7.58	7.42	7.45	4.66	5.52
Eu	2.55	2.27	2.22	2.53	2.12	2.35	2.40	2.36	2.40	1.58	1.84
Gd	6.10	6.37	6.24	6.90	5.91	6.43	6.59	6.47	6.52	4.59	5.30
Tb	0.89	0.93	0.92	0.99	0.87	0.91	0.94	0.93	0.86	0.73	0.75
Dy	4.41	4.43	4.51	4.55	4.10	4.21	4.35	4.29	4.28	3.73	4.14
Ho	0.90	0.84	0.91	0.83	0.77	0.77	0.79	0.79	0.71	0.76	0.76
Er	2.17	1.89	2.16	1.82	1.70	1.71	1.77	1.78	1.74	1.85	1.99
Tm	0.32	0.26	0.32	0.25	0.24	0.23	0.24	0.25	0.22	0.27	0.26
Yb	1.78	1.40	1.76	1.28	1.24	1.22	1.28	1.30	1.25	1.52	1.61
Lu	0.26	0.20	0.26	0.18	0.18	0.17	0.18	0.18	0.18	0.22	0.23
Hf	6.05	6.52	5.92	7.08	6.33	7.30	7.34	7.26	7.83	4.30	5.43
Ta	3.35	4.12	3.43	4.48	3.78	4.55	4.54	4.46	4.40	2.12	2.42
Pb	3.07	2.84	3.06	3.06	2.68	2.93	2.73	3.04	2.50	2.01	2.12
Th	2.85	2.90	3.00	3.22	2.51	3.25	3.20	3.14	2.86	1.41	1.66
U	0.80	0.97	0.85	1.08	0.86	1.10	1.09	1.07	1.04	0.45	0.55
La/Nb	0.61	0.52	0.62	0.54	0.49	0.51	0.52	0.52	0.49	0.56	0.58
Ba/Nb	101	6.36	15.5	7.02	6.14	7.30	7.38	7.54	7.74	12.2	10.9
Nb/U	66.6	66.4	66.1	65.8	67.6	65.0	63.8	64.7	67.7	71.5	70.1
Ce/Pb	21.6	23.5	23.2	25.2	21.7	25.4	26.8	24.1	28.7	18.9	21.8
La/Ce	0.49	0.50	0.49	0.50	0.49	0.49	0.49	0.49	0.48	0.47	0.49
Nb/La	1.63	1.91	1.62	1.86	2.03	1.94	1.92	1.93	2.04	1.79	1.72
Th/Ta	0.85	0.71	0.87	0.72	0.66	0.71	0.71	0.71	0.65	0.67	0.68

过程与矿产资源国家重点实验室用多接收等离子体质谱仪(MC-ICP-MS)测定，Hf 同位素在中国科学院地质与地球物理研究所用 MC-ICP-MS 分析，Sr-Nd-Hf 同位素的分馏分别采用 $^{86}Sr/^{88}Sr = 0.1194$，$^{146}Nd/^{144}Nd = 0.7219$ 和 $^{179}Hf/^{177}Hf = 0.7325$ 进行指数法校正，标样分析结果分别为：NBS-987 Sr 为 $^{87}Sr/^{86}Sr = 0.710245 \pm 16$，JNdi-1 Nd 为 $^{143}Nd/^{144}Nd = 0.512118 \pm 12$，Alfa Hf $^{176}Hf/^{177}Hf$ 为 0.282179 ± 4，NBS-981 Pb 标样得到 $^{206}Pb/^{204}Pb = 16.915 \pm 10$，$^{207}Pb/^{204}Pb = 15.465 \pm 9$，$^{208}Pb/^{204}Pb = 36.617 \pm 11$。样品分析结果见表 3。

3 分析结果

3.1 主量元素

在 TAS 图解(图 2)中，苏孟庄采集的玄武岩基本落在碱性系列中，顶层样品主要属于玄武岩，底层样品主要属于粗面玄武岩和碱玄岩/碧玄岩；应县采集的样品均落在亚碱性

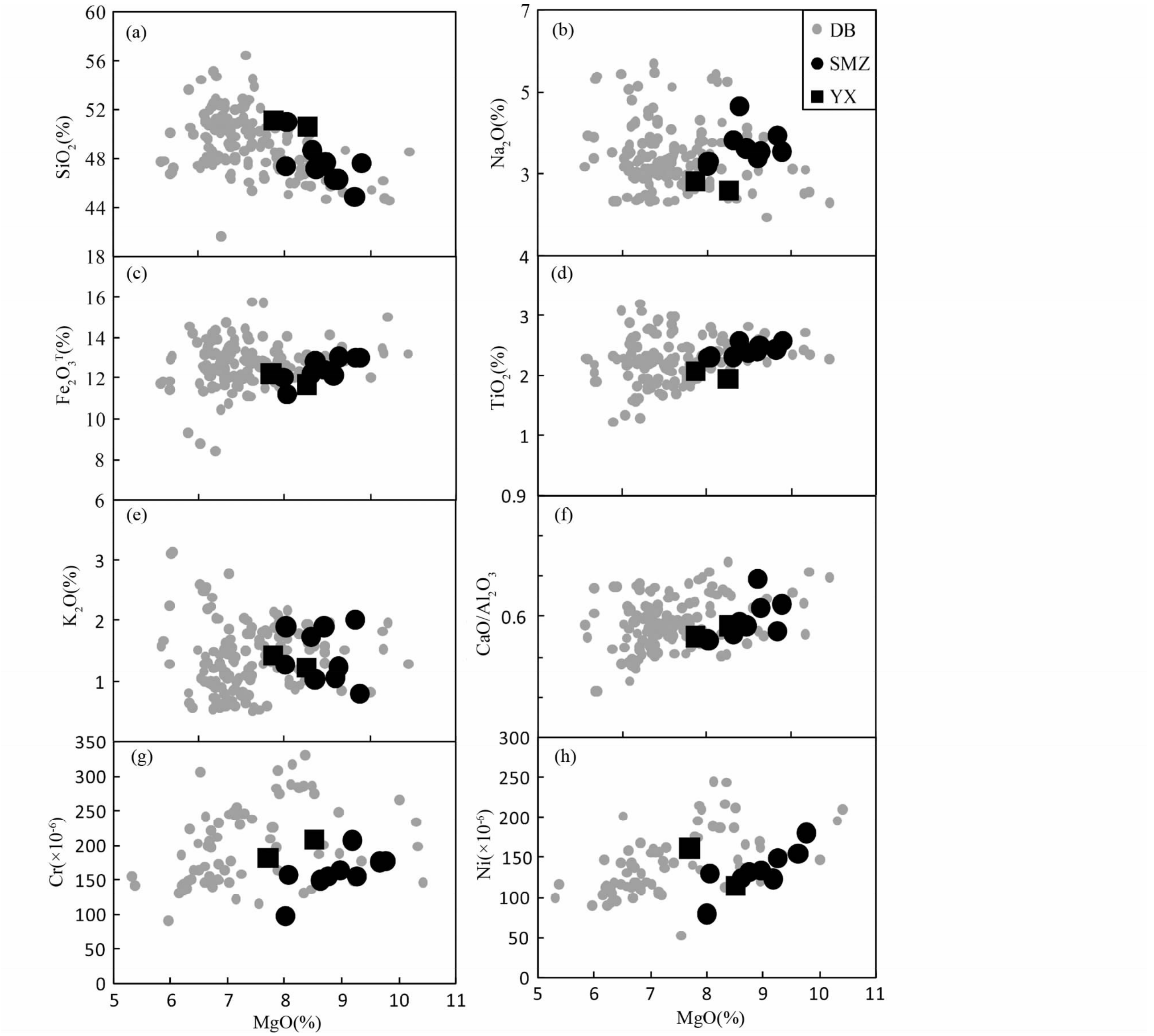

图3 繁峙新生代玄武岩主量元素氧化物及微量元素 Cr、Ni 对 MgO 的协和图

Fig. 3 Various oxides and Cr, Ni plotted against MgO for Cenozoic basalts in Fanshi with literature data plotted for comparison

表3 繁峙新生代玄武岩全岩 Sr-Nd-Pb-Hf 同位素组成

Table 3 Sr-Nd-Pb-Hf isotopic compositions of basalts from Fanshi

岩体	样品号	$\frac{^{87}Rb}{^{86}Sr}$	$\frac{^{87}Sr}{^{86}Sr}(2\sigma)$	$\frac{^{147}Sm}{^{144}Nd}$	$\frac{^{143}Nd}{^{144}Nd}(2\sigma)$	$\varepsilon_{Nd}(t)$	$\frac{^{208}Pb}{^{204}Pb}(2s)$	$\frac{^{207}Pb}{^{204}Pb}(2s)$	$\frac{^{206}Pb}{^{204}Pb}(2s)$	$\frac{^{176}Lu}{^{177}Hf}$	$\frac{^{176}Hf}{^{177}Hf}(2\sigma)$	$\varepsilon_{Hf}(t)$
苏孟庄	SMZ11-17	0.0639	0.704870±3	0.1268	0.512689±6	1.23	37.6±10	15.4±4	17.6±4	0.0060	0.282948±12	6.68
	SMZ11-24	0.0638	0.703848±3	0.1373	0.513057±4	8.36	37.8±11	15.4±4	17.9±5	0.0039	0.283001±12	8.60
	SMZ11-33	0.0491	0.703979±4	0.1295	0.512804±3	3.45	37.9±12	15.4±5	17.9±4	0.0035	0.282998±10	8.51
	SMZ11-36	0.0431	0.703937±2	0.1310	0.512904±2	5.40	37.9±8	15.4±3	17.9±3	0.0031	0.282996±10	8.42
应县	YX11-01	0.0712	0.704732±3	0.1430	0.512932±5	5.91	37.5±10	15.3±4	17.2±4	0.0071	0.282873±17	4.00
	YX11-04	0.0519	0.704398±3	0.1417	0.512617±3	−0.23	37.5±6	15.4±2	17.3±2	0.0059	0.282879±17	4.23

注：$\varepsilon_{Nd}(t)=\{[(^{143}Nd/^{144}Nd)_s-(^{147}Sm/^{144}Nd)_s\times(e^{\lambda t}-1)]/[(^{143}Nd/^{144}Nd)_{CHUR}-(^{147}Sm/^{144}Nd)_{CHUR}\times(e^{\lambda t}-1)]-1\}\times10^4$，其中，$(^{143}Nd/^{144}Nd)_{CHUR}=0.512638$，$(^{147}Sm/^{144}Nd)_{CHUR}=0.1967$，λ 为 $6.54\times10^{-12}a^{-1}$；$\varepsilon_{Hf}(t)=\{[(^{176}Hf/^{177}Hf)_s-(^{176}Lu/^{177}Hf)_s\times(e^{\lambda t}-1)]/[(^{176}Hf/^{177}Hf)_{CHUR}-(^{176}Lu/^{177}Hf)_{CHUR}\times(e^{\lambda t}-1)]-1\}\times10^4$，其中，$(^{176}Hf/^{177}Hf)_{CHUR}=0.282772$，$(^{176}Lu/^{177}Hf)_{CHUR}=0.0332$，λ 为 $1.867\times10^{-11}a^{-1}$；繁峙玄武岩用 $t=25.3$Ma 来校正

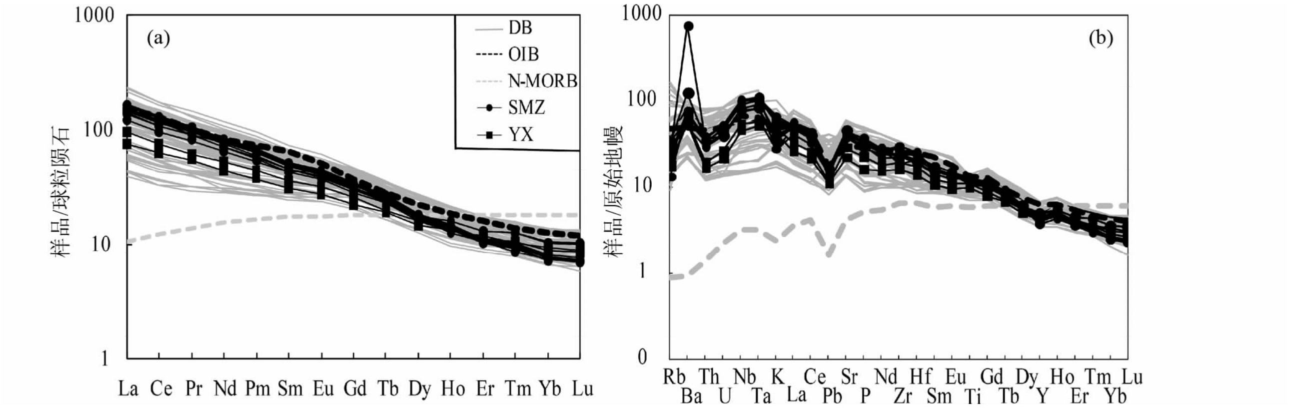

图 4 繁峙玄武岩稀土元素球粒陨石标准化配分图(a)和不相容元素原始地幔标准化蛛网图(b)

数据来源：原始地幔、球粒陨石、N-MORB、OIB(Sun and McDonough, 1989)，DB 为前人重力梯度带附近的新生代玄武岩数据(Tang *et al.*, 2006；马金龙和徐义刚, 2004；张文慧等, 2005；朱昱升等, 2012)

Fig. 4 Chondrite-normalized REE patterns (a) and primitive mantle normalized incompatible element diagrams (b) for basalts in Fanshi

Normalization values PM, CHUR, N-MORB and OIB after Sun and McDonough, 1989; DB after Tang *et al.*, 2006; Ma and Xu, 2004; Zhang *et al.*, 2005; Zhu *et al.*, 2012

系列中。因此本文认为苏孟庄玄武岩可能是多阶段喷发的结果，至少可分为重要的两层，顶层以碱性玄武岩为主，底层以粗面玄武岩为主，苏孟庄最底层样品几乎落在碱性系列和亚碱性的分界线上，可能暗示着一个由碱性到亚碱性的过渡转变。

繁峙玄武岩主量元素分析结果见表 1，其 SiO_2 含量介于 43.39% ~50.54%，TiO_2 为 1.92% ~2.54%，K_2O+Na_2O 值为 3.78% ~5.92%，Na_2O/K_2O 比值为 1.76 ~4.54，全铁 $Fe_2O_3^T$ 为 11.02% ~12.85%，$Mg^\#$ 为 55.6 ~60.0。从主量元素氧化物及微量元素对 MgO 的协和图中可以看出，SiO_2 与 MgO 呈简单的负相关关系，TiO_2、$Fe_2O_3^T$ 和 CaO/Al_2O_3 与 MgO 呈简单的正相关关系，Na_2O、K_2O 随 MgO 的降低变化不明显，微量元素 Cr、Ni 与 MgO 大致呈正相关关系(图 3)。此外，苏孟庄碱性玄武岩和应县亚碱性玄武岩在成分上存在差异，应县玄武岩的 SiO_2 含量相较苏孟庄偏高，TiO_2、Na_2O、P_2O_5 较苏孟庄玄武岩低，这可能与岩浆源区和熔融条件有关。

3.2 微量元素地球化学

繁峙玄武岩的稀土元素(REE)总量总体偏高，苏孟庄玄武岩为 149.7×10^{-6} ~192.8×10^{-6}，应县玄武岩为 103.1×10^{-6} ~123.0×10^{-6}，应县玄武岩相对苏孟庄明显偏低。稀土元素球粒陨石标准化配分图(图 4a)显示该地区玄武岩都具有 LREEs 富集，HREEs 亏损的特点，轻重稀土分馏明显，呈右倾模式，只是苏孟庄和应县的分馏程度不同，苏孟庄玄武岩 $(La/Yb)_N$ 为 13.3 ~21.6，$(La/Sm)_N$ 为 2.78 ~3.20，$(Gd/Yb)_N$ 为 2.79 ~4.30，而应县两样品的 $(La/Yb)_N<10$，$(La/Sm)_N<2.6$，$(Gd/Yb)_N<2.7$，苏孟庄玄武岩的分馏程度明显高于应县玄武岩。Sr、Eu 元素无亏损，Eu 甚至轻微富集，Eu/Eu^* ($Eu/Eu^*=(Sm+Gd)/2Eu$) 介于 1.00 ~1.21 之间。

原始地幔(PM)标准化微量元素蛛网图中(图 4b)，繁峙玄武岩显示了与洋岛玄武岩(OIB)类似的特征，随着元素不相容性的升高而富集。采样点的玄武岩均富集 Rb、Ba、Th、U、Sr 等大离子亲石元素(LILE)，不亏损 Nb、Ta、Zr、Hf 等高场强元素(HFSE)，且 Nb 和 Ta 相对富集。繁峙玄武岩的 Ce/Pb、Nb/U 比值较高，La/Nb、Ba/Nb 比值较低(图 5)，同样与 OIB 相似。以上微量元素特征暗示繁峙玄武岩与 OIB 具有相似的源区。

3.3 Sr-Nd-Pb-Hf 同位素特征

所测 6 个样品的 Sr 同位素比值较低($^{87}Sr/^{86}Sr$ = 0.703848 ~ 0.704870)，Nd、Hf 同位素比值较高，分别为 $^{143}Nd/^{144}Nd$ = 0.512617 ~0.513057 和 $^{176}Hf/^{177}Hf$ = 0.282873 ~0.283001，$\varepsilon_{Nd}(t)$ = - 0.23 ~8.36，$\varepsilon_{Hf}(t)$ = 4.00 ~8.60(表 3)。$^{87}Sr/^{86}Sr$-$^{143}Nd/^{144}Nd$ 图(图 6a)可以看出苏孟庄碱性玄武岩和应县亚碱性玄武岩投点均位于洋岛玄武岩(OIB)区域，接近全硅酸盐地球值(BSE)，投点总体呈负相关关系。$\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$ 图解(图 6b)中研究区样品基本投在 OIB 区域，全球阵列参考线附近，$\varepsilon_{Nd}(t)$ 与 $\varepsilon_{Hf}(t)$ 呈近似正相关关系。

6 个样品的 $^{206}Pb/^{204}Pb$ 比值在 17.2 ~ 17.9 之间，$^{207}Pb/^{204}Pb$ 和 $^{208}Pb/^{204}Pb$ 比值范围分别为 15.3 ~ 15.4 和 37.5 ~37.9，且苏孟庄碱性玄武岩 Pb 同位素比值整体高于应县亚碱性玄武岩。从 $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$ 图可见(图 7a)，碱性玄武岩基本落在印度洋 MORB 范围内，平行于北半球参照线(NHRL)，与汉诺坝玄武岩类似，亚碱性玄武岩则靠近五大连池岩体。在 $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ 图中(图 7b)，

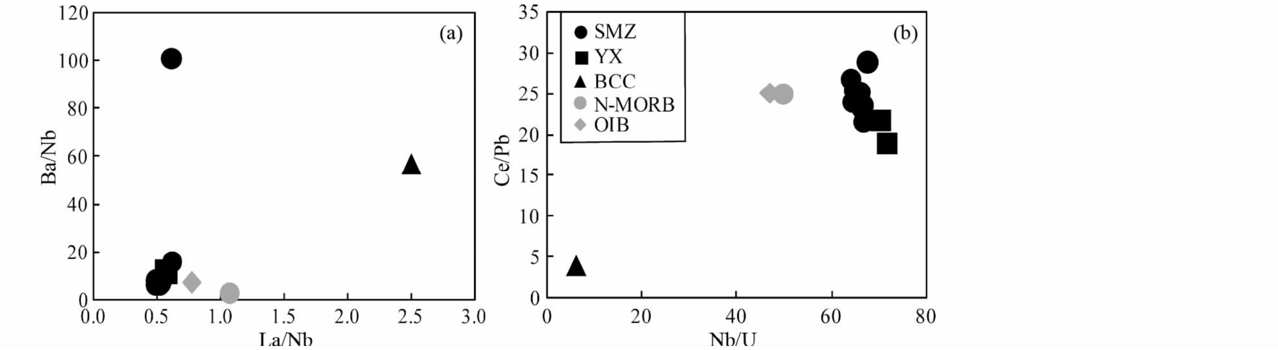

图5 繁峙玄武岩的 La/Nb-Ba/Nb (a)和 Nb/U-Ce/Pb(b)图解

数据来源:N-MORB、OIB(Sun and McDonough, 1989);BCC(Rudnick and Gao, 2003)

Fig. 5 La/Nb vs. Ba/Nb (a) and Nb/U vs. Ce/Pb (b) plots for the Cenozoic basalts

Data sources: N-MORB, OIB (Sun and McDonough, 1989), BCC (Rudnick and Gao, 2003)

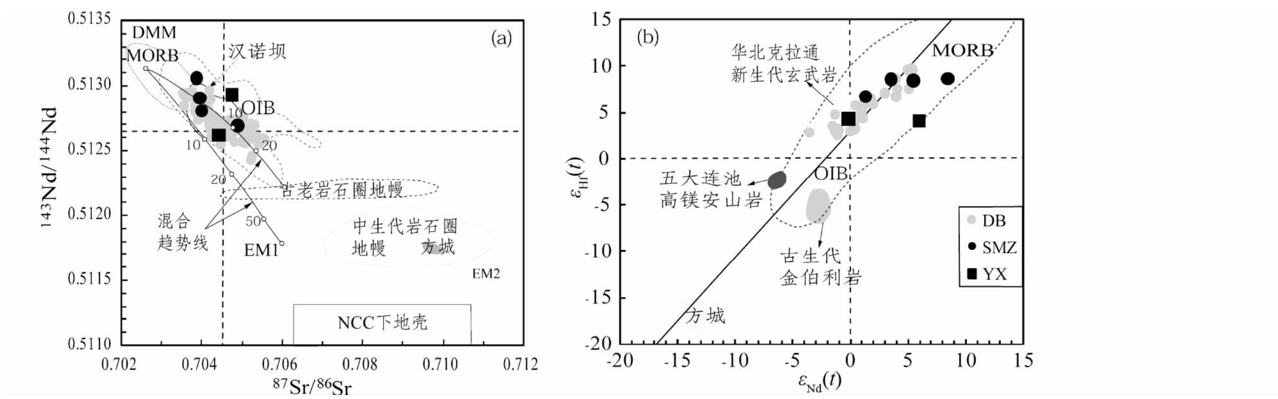

图6 繁峙新生代玄武岩的$^{87}Sr/^{86}Sr$-$^{143}Nd/^{144}Nd$图解(a)和$\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$图解(b)

图6a 中数据来源:汉诺坝玄武岩(Song *et al.*, 1990; Zhi *et al.*, 1990; Basu *et al.*, 1991; 解广轰和王俊文, 1992);白垩纪方城玄武岩、中生代岩石圈地幔和华北克拉通(NCC)岩石圈地幔(Zhang *et al.*, 2002);NCC 下地壳(Jahn *et al.*, 1999);MORB, OIB, EM1 和 EM2(Zindler and Hart, 1986);DB(Tang *et al.*, 2006; 马金龙和徐义刚, 2004; Xu *et al.*, 2005; 张文慧等, 2005; Zhang *et al.*, 2012a, b; 朱昱升等, 2012); 图6b 数据来源:中生代金伯利岩和中生代方城玄武岩(Zhang *et al.*, 2002);五大连池高镁安山岩(Zhang *et al.*, 2003), DB(Zhang *et al.*, 2012b; 朱昱升等, 2012);全球阵列参考线($\varepsilon_{Hf}=1.36\varepsilon_{Nd}+2.95$, Vervoort and Blichert-Toft, 1999)

Fig. 6 $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ (a) and $\varepsilon_{Nd}(t)$ vs. $\varepsilon_{Hf}(t)$ (b) diagrams for Fanshi Cenozoic basalts

Data sources in Fig. 6a: Hannuoba basalts (Song *et al.*, 1990; Zhi *et al.*, 1990; Basu *et al.*, 1991; Xie and Wang, 1992), Cretaceous Fangcheng basalts, Mesozoic lithospheric mantle and old lithospheric mantle beneath the NCC (Zhang *et al.*, 2002), lower crust of the NCC (Jahn *et al.*, 1999), MORB, OIB, EM1 and EM2 (Zindler and Hart, 1986); DB (Tang *et al.*, 2006; Ma and Xu, 2004; Xu *et al.*, 2005; Zhang *et al.*, 2005, 2012a, b; Zhu *et al.*, 2012); Data source in Fig. 6b: Paleozoic kimberlite and Mesozoic basalts from Fangcheng (Zhang *et al.*, 2002), Wulanhada high-Mg andisite (Zhang *et al.*, 2003); DB (Zhang *et al.*, 2012b; Zhu *et al.*, 2012); Reference Terrestrial Array ($\varepsilon_{Hf}=1.36\varepsilon_{Nd}+2.95$) is after Vervoort and Blichert-Toft (1999)

样品投点均落在 NHRL 附近。总体来说,繁峙玄武岩在同位素组成上与重力梯度带附近的新生代玄武岩有着相似的特征(Tang *et al.*, 2006; 马金龙和徐义刚, 2004; Xu *et al.*, 2005; 张文慧等, 2005; Zhang *et al.*, 2012a, b; 朱昱升等, 2012),都具有类 OIB 的同位素组成。

4 讨论

4.1 地壳混染作用

大陆背景下的地幔派生岩浆在上升喷发过程中会通过比大洋地区更厚的地壳,难免会受到不同程度地壳混染作用,因此所显现出来的地球化学特征要比大洋玄武岩更加复杂。但是观察表明地壳混染作用对繁峙玄武岩组成改变的影响可以忽略不计:(1)在苏孟庄底层新生代玄武岩中发现有橄榄岩包体,表明该地区的玄武岩是岩浆快速上升的结果,在地壳中停留的时间较短,因此在上升的过程中经历的地壳混染作用较小;(2)从繁峙新生代玄武岩的地球化学特征来看,繁峙新生代玄武岩具有与洋岛玄武岩以及汉诺坝玄武岩相似的地球化学特征,La/Nb-Ba/Nb 和 Nb/U-Ce/Pb 图(图5)显示繁峙玄武岩的不相容元素比值与 OIB、N-MORB

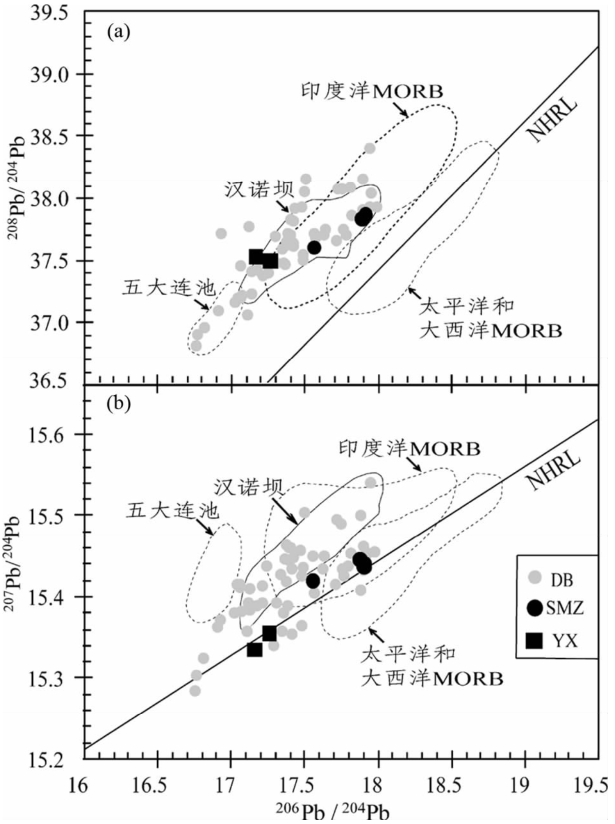

图 7　繁峙新生代玄武岩的 $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$（a）和 $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$（b）图解

数据来源：印度洋、太平洋和北大西洋 MORB（Barry and Kent，1998；Zou *et al.*，2000），NHRL（Hart，1984），五大连池玄武岩（Zhang *et al.*，1998；Zou *et al.*，2003）；DB 为前人重力梯度带附近的新生代玄武岩数据（Tang *et al.*，2006；张文慧等，2005；Zhang *et al.*，2012b）

Fig. 7　$^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$（a）and $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$（b）diagrams for the Fanshi Cenozoic basalts

Data sources：Indian MORB and Pacific and North Atlantic MORB（Barry and Kent，1998；Zou *et al.*，2000），NHRL（Hart，1984），Wudalianchi basalts（Zhang *et al.*，1998a；Zou *et al.*，2003），DB（Tang *et al.*，2006；Zhang *et al.*，2005，2012b）

相近，离全大陆地壳（BCC）投点较远，同样说明地壳混染不明显；(3)如果玄武岩在上升的过程中受到的地壳混染程度较高，将会赋予玄武岩较明显的“地壳特征”。平均全大陆地壳以 Nb、Ta、Ti 亏损为特征（Sun and McDonough，1989），较低的 Nb、Ta 含量，高的原始地幔标准化 Th/Nb 比值、低 Nb/La（<1）比值、明显 Nb、Ta、Ti 负异常的微量元素配分模式，是受到地壳混染的最鲜明的识别特征，但是从繁峙玄武岩中并没有观察到这些特征，繁峙玄武岩 Nb、Ta 富集、$(Th/Nb)_N = 0.34 \sim 0.45$、$(Nb/La)_N = 1.57 \sim 1.96$，微量元素蛛网图中 Nb、Ta、Ti 呈正异常，看不到“地壳特征”，因此可以排除地壳混染的重要性。

一般认为不含包体的玄武岩因上升速度较慢而在地壳中停留的时间较长，将能更高程度地同化地壳物质。应县亚碱性玄武岩及苏孟庄上层不含包体的碱性玄武岩的的 Nb、Ta 含量相对较低，可能暗示着地壳混染程度较苏孟庄底层玄武岩高。但是整个繁峙玄武岩的地球化学特征总体上都与地壳混染程度较小的 OIB 和汉诺坝玄武岩相似（Song *et al.*，1990；Zhi *et al.*，1990；Basu *et al.*，1991），表明地壳混染作用对繁峙玄武岩的地球化学特征的改变可忽略不计。

4.2　分离结晶作用

繁峙玄武岩的 Mg[#] 为 55.6 ~ 60.0，表明岩浆在演化过程中必然经历了一定程度的分离结晶作用。显微镜下观察到，苏孟庄玄武岩中含有橄榄石（ol）斑晶，斜长石（pl）微晶，应县玄武岩中含有橄榄石、单斜辉石（cpx）斑晶。在无水或少水条件下（如俯冲带岩浆作用条件），橄榄石和单斜辉石同时在液相线的结晶表明高压条件下的结晶分异作用，与岩石圈地幔条件岩浆房的推测一致。斜长石微晶是地表或近地表喷发时骤然降温冷却的结果。

微量元素蛛网图中（图 4b），Eu 和 Sr 没有明显的负异常，说明斜长石的分离结晶作用不明显，CaO/Al_2O_3 与 MgO 呈正相关关系，只是斜率较小，是单斜辉石分离结晶的结果。苏孟庄玄武岩的 Cr、Ni 随 MgO 的减小呈明显的下降趋势，表明苏孟庄玄武岩在上升过程中经历了橄榄石和单斜辉石的分离结晶。应县玄武岩的 MgO 含量相对较低，Cr、Ni 随 MgO 变化的趋势不明显，说明橄榄石和单斜辉石的分离结晶作用较苏孟庄玄武岩弱。这些演化趋势均与重力梯度带附近的玄武岩相似（Fan and Hopper，1991；Basu *et al.*，1991；Tang *et al.*，2006；马金龙和徐义刚，2004；Xu *et al.*，2005；张文慧等，2005；Zhang *et al.*，2012a，b；朱昱升等，2012），因此，该地区的岩浆演化过程中橄榄石和单斜辉石是常见的分离结晶矿物。

4.3　岩浆源区

繁峙玄武岩的主微量组成、Ba/Nb、La/Nb 和 Ce/Pb 等比值以及 Sr-Nd-Pb-Hf 同位素组成均与 OIB 及汉诺坝玄武岩相似（Song *et al.*，1990；Zhi *et al.*，1990；Basu *et al.*，1991；解广轰和王俊文，1992），表明研究区玄武岩的源区与 OIB 及汉诺坝玄武岩相似，可能均起源于软流圈地幔。结合前人的研究发现，汉诺坝、大同、集宁、阳原、鹤壁新生代玄武岩同样具有该特征（Song *et al.*，1990；Zhi *et al.*，1990；Basu *et al.*，1991；Tang *et al.*，2006；马金龙和徐义刚，2004；Xu *et al.*，2005；张文慧等，2005；Zhang *et al.*，2012a，b；朱昱升等，2012），推断重力梯度带附近的这些新生代玄武岩可能起源于同一软流圈地幔源区。

繁峙玄武岩的地幔源区物质比 OIB、原始地幔更富集不相容元素（Sun and McDonough，1989），$(La/Sm)_{繁峙玄武岩源区} > (La/Sm)_{OIB源区} > (La/Sm)_{PM}$，并且越不相容的元素越富集（图 4b），OIB 的这种富集特征被认为是洋壳物质（Hofmann and White，1982）、陆源沉积物（White and Duncan，1996；

Weaver, 1991)或者大陆岩石圈物质(McKenzie and O'Nions, 1983, 1995)加入到了源区的结果。然而循环洋壳(如$(La/Sm)_{PM}<1$)太亏损,陆源沉积物地壳特征(富集 Pb,亏损 Nb、Ta、P 和 Ti)太明显,都不适合作为 OIB 的源区物质(Niu and O'Hara, 2003; Niu *et al.*, 2011),因此岩石圈底部和地震波低速带(LVZ)顶部交界处富集组分以及岩石圈中的富集岩脉对熔体的交代作用是造成 OIB 富集特征最有可能的原因(Lambert and Wyllie, 1970; Niu and O'Hara, 2003, 2007①; Pilet *et al.*, 2005; Niu *et al.*, 2011)。对于远离板块边界的大陆背景下的玄武质岩浆作用,可能也存在类似的地幔交代作用。中国东部之下的地震波层析成像图显示:在中国东部之下 410~660km 过渡带内存在冷的太平洋俯冲板块,其中的挥发分和富集不相容元素的熔体在浮力的作用下会聚集在 LVZ 顶部,还有一些甚至上升结晶出液相线矿物加入橄榄岩围岩,形成"堆晶"岩脉。软流圈地幔在上涌的过程中会与这些富熔体层和岩脉发生交代作用,使喷发的岩浆相比之前更加富集(O'Reilly and Griffin, 1988; Niu, 2008; Niu *et al.*, 2012)。

Sr-Nd-Hf(图 6)以及 Pb 同位素图解(图 7)可以看出:繁峙玄武岩同位素呈现亏损的特征,但与 MORB 相比,其 Sr 同位素比值相比较高,Nd、Hf 同位素比值相比较低,主要分布在 OIB 范围内,同位素都呈较良好的线性关系,这与中国东部的其他地区的新生代碱性玄武岩相似(Zhou and Armstrong, 1982; Zhang *et al.*, 2009; Wang *et al.*, 2011b),表明至少有两个地幔端元参与了繁峙玄武岩的成岩作用,即亏损地幔和富集地幔组分。亏损地幔指的是软流圈地幔可能还包括新生的岩石圈地幔,但是后者在没有更高温、新热源的情况下不参与岩浆作用;富集地幔组分可能是 EM1 (Zhou and Armstrong, 1982; Zhi *et al.*, 1990)或者 EM2(Zou *et al.*, 2000)。对太行山地区玄武岩中携带的地幔橄榄岩包裹体以及中生代辉长岩的研究表明:太行山地区之下的岩石圈厚度约 80~100km(Ma, 1989),且之下的岩石圈地幔具有类 EM1 型富集地幔特征,可能是经富集、交代后的古老岩石圈的残余(Tatsumoto *et al.*, 1992; Gao *et al.*, 2002; Zhang *et al.*, 2004; 汤艳杰等, 2004; Tang *et al.*, 2006, 2012; Rudnick *et al.*, 2006; Wang *et al.*, 2006; Huang *et al.*, 2012),因此,我们推断参与繁峙玄武岩成岩作用的富集端元极有可能是繁峙地区之下的具有 EM1 型特征的古老岩石圈地幔。但是华北克拉通之下的古老岩石圈地幔经历了大程度熔体的抽离,很难熔融生成大量镁铁质岩浆,因此,古老克拉通岩石圈地幔不可能是大陆玄武岩的主要源区。我们根据 Sr-Nd 同位素二端员混合模拟(图 6a)得出富集组分 <10%。

因此,我们推断繁峙新生代玄武岩主要起源于软流圈地幔的部分熔融,但存在软流圈-岩石圈的相互作用:少量 EM1 型古老岩石圈地幔的加入解释了繁峙玄武岩同位素总体上亏损,但相比 MORB 富集的特征,吸收岩石圈底部的富熔体层和同化岩石圈中早期形成的交代岩脉解释了不相容元素富集的特征。

4.4 熔融程度与深度

玄武岩的硅饱和程度和熔融深度有关(Green and O'Hara, 1971; DePaolo and Daley, 2000),实验岩石学得出硅不饱和的碱性岩浆产生的压力要高于硅饱和的拉斑玄武岩浆(Green and O'Hara, 1971; Falloon *et al.*, 1988; Kushiro, 2001)。一般认为华北的碱性玄武岩的源区压力为 25~30kbar(>80km),拉斑玄武岩的源区压力为 15~20kbar (50~60km; Nohda *et al.*, 1991)。苏孟庄玄武岩皆为碱性玄武岩,应县玄武岩为亚碱性玄武岩,且苏孟庄玄武岩相比应县玄武岩的 SiO_2 的含量较低,LREE 丰度较高,LREE/HREE 值较大,暗示着苏孟玄武岩的熔融深度较应县玄武岩大。这种熔融深度的差异可能来自于地幔源区的不均一性,也可能来自于岩石圈的厚度的差异(Niu *et al.*, 2011)。

繁峙新生代玄武岩明显富集轻稀土元素,轻重稀土分馏明显,$(La/Yb)_N$ 为 8.42~21.60,呈明显的右倾模式,且苏孟庄玄武岩相比应县玄武岩分馏程度更加明显,表明繁峙玄武岩都起源于以石榴子石二辉橄榄岩为主的较深的深度,且苏孟庄玄武岩的熔融深度较应县玄武岩大。因为对于石榴子石,Yb 是相容元素,而 La、Sm 为不相容元素,石榴子石相橄榄岩部分熔融的程度越低,分异程度越明显;而在尖晶石相橄榄岩部分熔融作用中,La/Yb 变化较小、Sm/Yb 基本不变,因此 La/Yb-Sm/Yb 图常用于区分来自石榴子石相橄榄岩和尖晶石相橄榄岩的玄武岩(Niu *et al.*, 1996; Xu *et al.*, 2005)。从繁峙玄武岩的 La/Yb-Sm/Yb 图中(图 8a)可以看出,苏孟庄玄武岩和应县玄武岩都投在石榴子石二辉橄榄岩熔融模拟曲线上,且苏孟庄玄武岩较应县玄武岩的熔融程度低,苏孟庄约为 1%~3%,应县玄武岩约为 3%~5%。

高度不相容元素的比值可用于示踪岩石形成的过程。地幔岩浆作用过程中 Zr 相对于 Y 更不相容,不相容元素 Zr/Y 比值受部分熔融程度的影响,但基本不受分离结晶作用的影响,熔融程度越低,Zr/Y 比值越高(Nicholson and Latin, 1992)。Zr-Zr/Y 图中(图 8b),样品所投的点相关性良好,具有一定的斜率,这说明研究区玄武岩主要起源于地幔物质的部分熔融,样品间化学组分的差异可能来源于不同深度地幔物质的不同程度的部分熔融和源区物质的不均一性。苏孟庄玄武岩样品的 Zr/Y 比值整体比应县的高,说明苏孟庄玄武岩的熔融程度较应县低,与 La/Yb-Sm/Yb 图得出的模拟计算结果一致。

① Niu YL and O'Hara MJ. 2007. "Mantle plumes" are NOT from ancient oceanic crust. http://www.mantleplumes.org/NotFromCrust.html

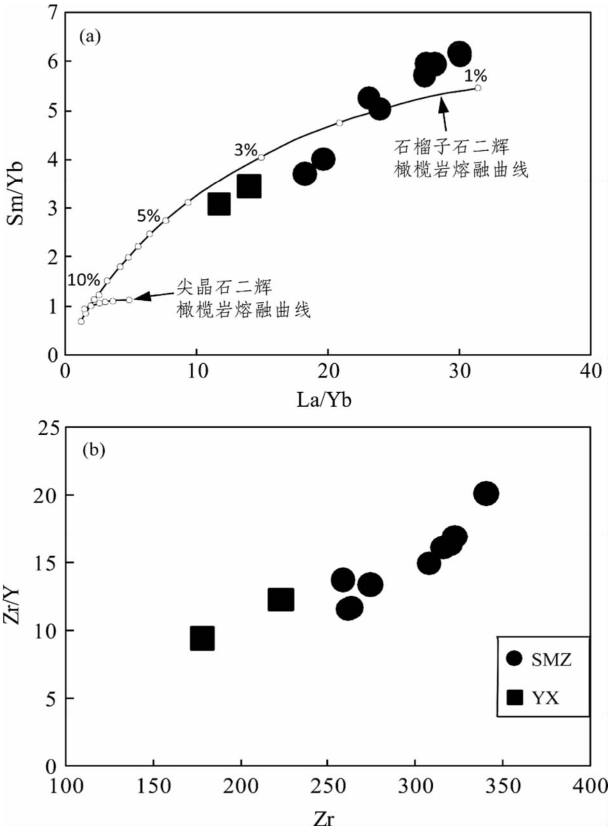

图 8 La/Yb-Sm/Yb 图(a)和 Zr-Zr/Y 图(b)用于判别岩浆的成岩过程

(a)图中：曲线旁数字代表熔融比例；源岩矿物组分和矿物熔融比例数据引自 Johnson *et al.*（1990），元素分配系数据引自 McKenzie and O'Nions(1991)

Fig. 8 La/Yb vs. Sm/Yb (a) and Zr vs. Zr/Y (b) for Fanshi basalts

In Fig. 8a: the number near the curve are melting ratio; Source rock mineral composition and mineral melting rate after Johnson *et al.* (1990) and element distribution coefficient data after Mckenzie and O'Nions (1991)

5 地幔动力学机制

华北克拉通岩石圈减薄和广泛分布的中、新生代玄武岩一直是研究的热点，其动力学机制更是备受关注。地幔柱模型、断裂模型、热化学侵蚀、岩石圈拆沉都是可能的机制，但也都存在着一定的争议。中国东部的地震波层析成像表明：在中国东部之下的 410 ~ 660km 之间的过渡带内存在水平向西延伸的冷的古太平洋俯冲板片（Kárason and Van der Hilst, 2000; Pei *et al.*, 2004; Zhao, 2004; Zhao *et al.*, 2004），该板块阻止下地幔的热地幔上涌，不利于上地幔内热地幔柱的形成，因此，用地幔柱模型解释中国东部中、新生代火山活动不具有说服力（Niu, 2005）。同时，该冷的板块需要从其上部和下部吸收热量达到热均衡，也没有过剩热量支持热侵蚀作用（Griffin *et al.*, 1998; Menzies and Xu, 1998; 徐义刚, 1999; Xu, 2001; Xu *et al.*, 2004, 2005）。岩石圈拆沉可以较好地解释岩石圈的减薄和新生代玄武岩的地球化学特征（Gao *et al.*, 1998, 2004, 2008, 2009; Xu *et al.*, 2006, 2009, 2010），但是缺少直观的物理学理论解释上浮的岩石圈地幔是如何下沉到高密度的软流圈地幔中。拉张断裂和被动上涌减压熔融模型将未知成因的盆地的存在作为中国东部拉张的证据（Davis and Darby, 2010; Wang *et al.*, 2011a, 2012）也是危险的（Niu, 2005）。因此，华北克拉通的岩石圈减薄和中、新生代火山活动的形成机制尚未定论，还需要进一步探讨。

太行山重力梯度带形成于早白垩纪，东西两侧在地貌、地壳厚度、岩石圈厚度、地表热流值均存在明显的差异（Xu, 2007）。太行山重力梯度带的东西两侧陡峭的梯度差异允许我们对重力梯度带附近的新生代玄武岩的成因有新的推测：软流圈由西向东的流动越过重力梯度带时由于岩石圈骤然减薄（岩石圈-软流圈界面从西部的 ~ 150km 变浅为东部的 ~ 80km）必然会发生减压熔融，形成玄武质岩浆（Niu, 2005），断裂的活动与再活化为岩浆的侵入提供了通道，可形成重力梯度带附近广泛分布的新生代火山作用。如果该模型成立，那我们必须思考，什么动力学机制驱动软流圈向东的流动呢？有以下几种观点：

（1）与印度-欧亚板块碰撞有关；印度板块向北俯冲于欧亚板块之下，推挤作用推动鄂尔多斯块体的逆时针旋转，促使太行山地区岩石圈拉张减薄，造成软流圈物质上涌产生玄武岩浆作用（Ren *et al.*, 2002; Zhang *et al.*, 2003; Tang *et al.*, 2006）。此外，印度板块以 40mm/y 的速度向欧亚板块之下俯冲，> 50Ma 的连续不断的物质注入必然会驱动软流圈地幔侧向流动（Liu *et al.*, 2004），但是 Zhao *et al.* (2011) 根据地球物理资料得出太行山地区岩石圈下部的上涌地幔流与印度-欧亚碰撞无关。

（2）与太平洋的向西俯冲有关；地震波层析成像图显示：在中国东部之下 410 ~ 660km 过渡带内存在冷的太平洋俯冲板块，其西端水平延伸至太行山重力梯度带之下（Kárason and Van der Hilst, 2000; Pei *et al.*, 2004; Zhao, 2004; Zhao *et al.*, 2004）。西太平洋俯冲带是全球最大的俯冲带之一，板块向下俯冲，俯冲带上部地幔楔必须有新物质补给，产生"楔吸力"，驱动中国大陆之下的软流圈东流，造成更远的西部软流圈向中国东部之下流动，因为东西岩石圈厚度在重力梯度带处的差异，西部软流圈东流必然会引起减压熔融，形成中国东部的玄武质火山作用（Niu, 2005）。

太行山重力梯度带恰好位于印度-欧亚板块碰撞带和西太平洋俯冲带这两种构造域的边界（Xu, 2007），因此造成这种软流圈东流的驱动力到底是受单一机制的影响还是两种机制的共同作用还需要进一步的研究。

6 结论

通过对繁峙玄武岩的元素和同位素地球化学特征的研

究，我们得出以下几点结论：

(1)繁峙苏孟庄碱性玄武岩和应县亚碱性玄武岩均具有类 OIB 的地球化学特征，与重力梯度带附近的汉诺坝、大同、阳原、集宁、鹤壁等地区新生代玄武岩相似，表明它们可能起源于同一软流圈地幔源区的部分熔融，且存在一定程度的软流圈-岩石圈相互作用。

(2)岩浆在上升的过程中，地壳混染作用可忽略不计，岩浆演化过程中橄榄石和单斜辉石是常见的分离结晶矿物。

(3)模拟计算得出苏孟庄碱性玄武岩的熔融程度较小，熔融深度较大；而应县亚碱性玄武岩的熔融程度较大，熔融深度较小。该熔融深度的差异可能受熔融环境和深大断裂的影响。

(4)重力梯度带附近的新生代的火山活动推测与软流圈的向东流动有关，其驱动力可能是太平洋俯冲板块的楔吸力，也可能是印度板块向欧亚板块的俯冲的物质补给，或者两者兼而有之，该地区广泛分布的断裂带可能为岩浆上涌提供了通道。

致谢 野外工作得到了高军平老师、付飘儿、孙文礼的协助；样品分离测试工作得到了文中所提实验室老师及相关人员的极大支持与帮助；审稿人认真阅读了本文，并提出宝贵的修改意见；在此一并表示衷心的感谢！

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